



Evaluation of Short-Beam Shear Strength, Acoustic and Vibrational Performance of Chemically Treated Banana Fiber Reinforced Carbon–Kevlar Hybrid Composites

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ABSTRACT : This study results in evaluation of short-beam shear strength, acoustic and vibrational performance of chemically treated banana fiber reinforced carbon–kevlar hybrid composites. Banana fibers were treated with 5 % NaOH and 0.5 % KMnO₄ to improve fiber surface characteristics and interfacial bonding within a sandwich laminate of carbon–Kevlar intra-ply skins and banana fiber core fabricated by hand lay-up and compression moulding. Short-beam shear strength (SBSS) increased from 14.27 MPa in untreated composites to 17.65 MPa and 19.52 MPa with KMnO₄ and NaOH treatments, respectively, due to enhanced fiber matrix adhesion and removal of surface impurities. Vibrational analysis showed untreated composites had low stiffness (7780.23 N/m) and damping ratio (0.00716), whereas NaOH treatment increased stiffness (9480.51 N/m) and natural frequency (28.68 Hz), improving rigidity and moderate damping. KMnO₄-treatment yielded the highest damping ratio (0.0557) with reduced stiffness, favouring vibration energy dissipation. Acoustic tests revealed KMnO₄-treated composites have superior sound transmission loss across low to middle frequencies, peaking at 15.5 dB at 50 Hz, indicating effective acoustic insulation linked to better mechanical damping. Scanning electron microscopy confirmed enhanced fiber impregnation and fewer defects after treatments. These findings highlight the significant role of chemical surface modification in optimizing structural integrity, vibration control, and acoustic insulation in sustainable banana fiber/carbon–Kevlar hybrids. The improved multifunctional properties suggest promising applications in aerospace, automotive, and structural fields requiring lightweight, durable, and sound-mitigating materials.

KEYWORDS: banana fiber; Kevlar-carbon intra-ply; free vibration; acoustic properties; inter-laminar shear strength; short-beam shear strength

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I. INTRODUCTION

Composite materials are engineered materials created by combining two or more different components. Their combination results in a new material displaying improved properties compared to the components ((Okoronkwo et al. 2025), (Okoronkwo et al. 2024), (Okoronkwo et al. 2022), (Okoronkwo et al. 2021), (Okoronkwo et al. 2019)). Composite materials’ unique properties make them crucial in many industries, such as the aerospace, automobile, marine, and building sectors. Their use presents numerous engineering and manufacturing benefits, including an improved strength-to-weight ratio, resistance to corrosion, flexible design options, and higher durability when compared to standard materials ((Madu et al. 2019), (Madu et al. 2020) and (Ezeokpube et al. 2021)). Traditionally, human-made fibers have been the preferred choice for reinforcement due to their strength, longevity, and affordability. Nevertheless, the materials also pose an environmental concern by being the source of micro-plastic pollution. Due to the growing concern about sustainability, the development of natural-fiber-reinforced composites has ensued. Natural fiber composites (NFCs) are increasingly being applied in numerous areas as they bring together lightness in combination with strength ((Rajendran et al. 2025), (Mohanraj et al. 2025)). In addition, they possess superior mechanical properties in the form of specific strength and modulus along with exceptional sound absorption characteristics. Their flexibility, green profile, and biodegradability justify them as an attractive option for today’s industrial applications ((Chokshi et al. 2022), (Fernandes et al. 2024), (Pai et al. 2023)).

Plant fibers come from various parts of the plant, for instance, stems (such as banana, hemp, and jute), leaves, seeds, and roots, and are characterized by the high content of cellulose. Among them, banana fiber composites have received interest in the manufacturing sector due to their diverse properties as well as their green characteristics ((Palanisamy et al. 2024), (Temitayo et al. 2023), (Nguyen et al. 2022)). Banana fiber extraction occurs from the pseudo-stem of the banana plant due to being lightweight, having high strength values, as well as being renewably sourced, positioning it as a potential substitute for the use of conventional petroleum-based materials. Nevertheless, banana fiber exhibits little deformation ability, hence being unsuitable for bearing substantial deformation before rupturing. In order to enhance strength as well as durability, banana fiber can be chemically treated or combined with other fibers such as glass, carbon, or synthetic polymers in composite blends. In combined use with resin or other strengthening materials, the composite product made of the banana fiber finds use in load-bearing parts due to its lightweight nature as well as in interior panels used for insulating materials. Future prospects indicate opportunity for the use of banana fiber composites in sustainable aviation as ecofriendly products satisfying both performance as well as environmental requirements ((Chokshi et al. 2022), (Sivaranjana et al. 2021), (Chenrayan et al. 2023)).

Banana fibers are natural fibers that inherently possess surface impurities such as lignin, hemicellulose, waxes, and pectin, which contribute to their rigidity and hydrophilic nature. To improve their mechanical performance and compatibility with polymer matrices in composite applications, banana fibers undergo chemical treatments ((Chenrayan et al. 2023), (Komal et al. 2023), (Cuebas et al. 2021)). Alkaline treatment, commonly using sodium hydroxide (NaOH), is widely employed to remove these non-cellulosic materials, increase the cellulose content, and roughen the fiber surface. This process enhances fiber flexibility, reduces moisture absorption, and significantly improves tensile strength by increasing fiber–matrix interfacial adhesion. Other chemical treatments, such as potassium permanganate (KMnO₄), may be used for surface modification to further optimize fiber bonding and strength ((Kudva et al. 2024), (Kudva et al. 2024)). Overall, chemical treatments are essential for transforming raw banana fibers into effective reinforcement materials for composites by enhancing their physiochemical properties and mechanical behaviour. Table 1 presents a summary of chemical treatments applied to banana fibers along with their corresponding effects on the mechanical properties of the composites.

Table 1 : Literature review on banana fiber treatment

Author & Year	Work Carried Out	Findings
(Komal et al. 2020)	Composites containing banana pseudo-stem (BPS) fibers treated with a 5% (w/v) aqueous sodium hydroxide (NaOH) solution	The composite showed approximate improvements of 4% in tensile strength, around 5% in flexural strength, and about 12% in impact strength
(Cuebas et al. 2021)	Banana fibers were subjected to alkali treatment by soaking in 5% sodium hydroxide solution (w/v)	The FTIR test revealed a reduction in hydroxyl (OH) groups, indicating increased hydrophobicity and improved mechanical properties
(Chenrayan et al. 2023)	Chopped fibers were treated with 5% alkaline	The flexural characteristics of sandwich specimens

	solution (NaOH)	containing 10% banana fiber were higher than the neat epoxy core
(Fajardo et al. 2024)	Banana fibres were soaked in 5% NaOH for 1h at room temperature with stirring, then washed with acetic acid and water to remove NaOH residues	FTIR confirmed the removal of non-cellulosic components, while SEM revealed increased surface roughness due to impurity removal; interfacial shear strength improved by 10% over untreated fibers
(Nguyen and Nguyen 2022)	Banana fibers were treated with NaOH solutions at various concentrations	SEM analysis revealed enhanced fiber bonding and wetting properties for 5% NaOH-treated fibers
(Kadire and Joshi 2024)	Banana fibers treated with 2%, 5%, and 7% (w/v) NaOH concentrations	A 5% NaOH treatment lowered water absorption and increased tensile, bending, and low velocity impact strengths of the composite by approximately 15 %, 9 %, and 30%, respectively

While the mechanical improvements afforded by these treatments are well-documented, there remains a relative paucity of research on how such chemical modifications affect the free vibration and acoustic properties of banana fiber composites. Enhanced fiber–matrix bonding and reduced microstructural defects through chemical treatment are expected to improve vibration damping and sound absorption characteristics, key factors for multifunctional applications in automotive and construction industries ((Kuppuraj et al. 2022), (Rouf et al. 2025), (Senthilrajan et al. 2025)). The aim of this study is to fill this research gap by investigating the influence of controlled NaOH and $KMnO_4$ treatments on the acoustic and free-vibration characteristics of banana fibre composites, advancing their potential for noise reduction and vibration control in green composite materials.

Combining banana fibers with carbon–Kevlar intra-ply fibers makes the hybrid composite a promising material for high-performance industries. This combination combines of eco-friendly, lightweight, and biodegradable advantages of banana fibers with the impact resistant qualities of carbon and Kevlar fibers ((Agarwal et al. 2024), (Agarwal et al. 2022), (Agarwal et al. 2023)). Table 2 presents studies related to the acoustic and free-vibration properties of banana fiber composites.

Table 2: Overview of the available literature on free-vibration and acoustic behaviour of banana fiber composites

Author & Year	Work Carried Out	Findings
(Kuppuraj et al. 2022)	Banana/sisal epoxy hybrid, grapheme fillers (varying wt %), hand lay-up	Natural frequency up to 100 Hz (Mode 1), damping factor 0.0883, dense hybrid structures expected to provide good sound absorption
(Singh et al. 2022)	Banana fiber–polypropylene matrix, alkali-treated, impedance tube measurement	Noise reduction coefficient (NRC) 0.78 for 4500 gsm multilayer samples, max. transmission loss 23 dB
(Sagar et al. 2022)	Influence of NaOH treatment and PLA coating on jute/banana hybrid composites	Tensile strength +20.56%, flexural strength +16.7% (related to improved vibrational behaviour)
(Agarwal et al. 2024)	Intraply layers consisting of carbon and Kevlar as surface layers and three layers of basalt as core subjected to mechanical tests	Hybrid laminates exhibited a maximum impact strength of 136.25 kJ/m ² , marking a 24.4 % increase compared to basalt composites; enhancement in impact toughness is credited to the incorporation of surface intraply layers
(Senthilrajan et al. 2025)	Effect of surface modification on vibration and acoustic properties	NaHCO ₃ treatment highest natural frequency 61 Hz, improved damping, max. sound absorption coefficient 0.67 at ~2 k Hz, 69 % higher than untreated
(Lokesh et al. 2025)	Calamus rotang/glass fiber hybrid composites including banana fiber reinforcement	Damping ratio peak at 8% fiber loading, Sound absorption improved with hybrid fibers
(Rouf et al. 2025)	Alkali-treated banana fibers up at 0–24 wt % in epoxy matrix	Vibration damping improves to ~15–20% with 24 wt % fibers

While hybrid composites have been extensively studied, limited attention has been given to the hybridization of chemically treated banana fibers with intra-ply carbon–Kevlar laminates focusing on their free-vibration and acoustic behaviour. Earlier works primarily explored banana fibers in combination with synthetic reinforcements such as glass, carbon, or aramid, but little emphasis was placed on their use in intra-ply fiber configurations. The present study addresses this gap by applying controlled NaOH (5 %) and KMnO_4 (0.5 %) treatments to banana fibers, integrating them within intraply carbon–Kevlar laminates, and conducting comprehensive free-vibration and acoustic tests to evaluate their performance—thereby advancing the design of multifunctional hybrid composites with enhanced dynamic and noise attenuation capabilities.

This study uniquely integrates mechanical, acoustic, and vibrational analyses of chemically treated banana fiber/carbon–Kevlar hybrid composites, which remains limited in current literature.

II. MATERIALS AND METHODS

2.1. Materials

The materials employed in this investigation were banana fiber and carbon – Kevlar intraply fibers along with epoxy LY556 resin and HY951 hardener with the mixing ratio of 100:35. The banana fibers used for the investigation were obtained from local Agricultural and food market at Owerri, Imo State. The twill woven bi-directional carbon – Kevlar hybrid fabric were obtained from Ikenna Chemicals Ltd., Owerri, Imo State. Figure 1 shows the banana and carbon – Kevlar intra-ply fibers used for the fabrication. Table 3 shows the details of the properties of the fiber used.

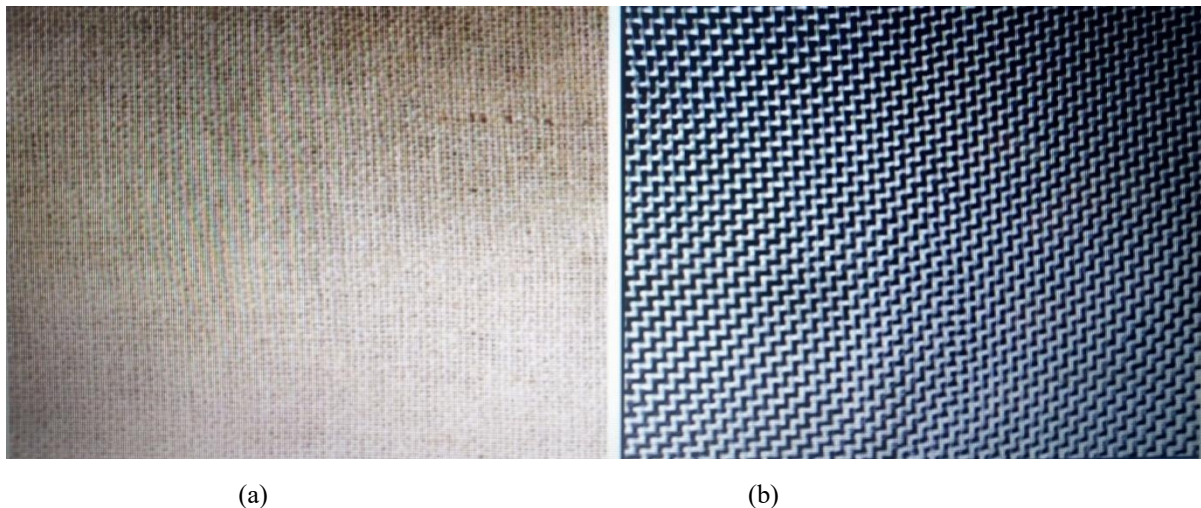


Figure 1: Materials used: (a) banana fiber; (b) carbon–Kevlar intraply fiber.

Banana fibers were subjected to two independent chemical treatments to enhance surface characteristics and interfacial bonding, as shown in Figure 2. In the first method, fibers were treated with a 0.5 % sodium hydroxide (NaOH) solution for 2 h at room temperature. This alkali treatment effectively removed non-cellulosic materials such as hemicellulose, lignin, pectin, and waxes, leading to increased cellulose exposure, micro-fibril alignment, and improved surface roughness. After treatment, the fibers were subjected to distilled water wash until a neutral pH was obtained and then oven-dried at 60 – 70° C. In the second method, a 0.5 % potassium permanganate (KMnO_4) solution was used, and fibers were immersed for 3 min. The oxidizing action of KMnO_4 degraded traces of lignin, created micro-voids, and increased surface energy, thereby enhancing the potential for mechanical interlocking with epoxy resin. Following treatment, the fibers were washed with distilled water to remove residual chemicals and subsequently oven-dried at 60 – 70° C. Both treatments improved the surface morphology and fiber–matrix adhesion, though by distinct chemical mechanisms.

Table 3: Details of reinforcements used.

Type of Fiber	Weave Pattern	Aerial Density (Grams per Square Meter)	Thickness (mm)	Filament Count
Banana fiber mat	Plain weave	250	0.3	3K
Carbon-aramid intraply mat	Twill weave	300	0.35	-



Figure 2: Chemical treatments: (a) 5 % NaOH, (b) 0.5 % KMnO₄. (c) Hand lay-up method.

2.2. Laminate Fabrication

The hybrid laminate with dimensions 300 mm × 300 mm was fabricated using the hand lay-up method followed by compression moulding. The stacking sequence used was three layers of banana fibers sandwiched between intraply carbon – Kevlar surface layers, as presented in Figure 3.

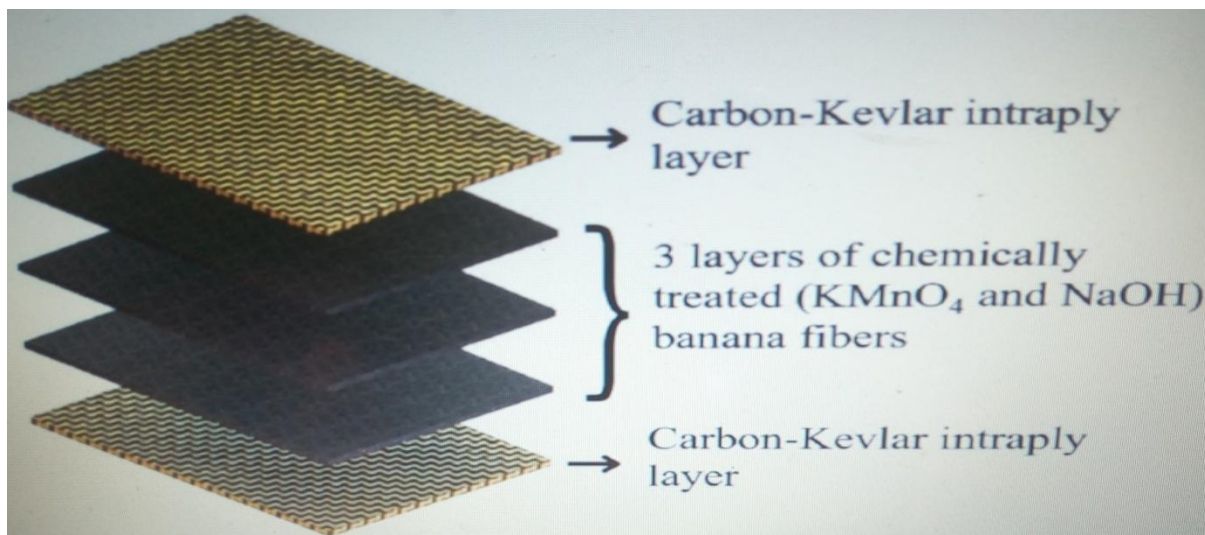
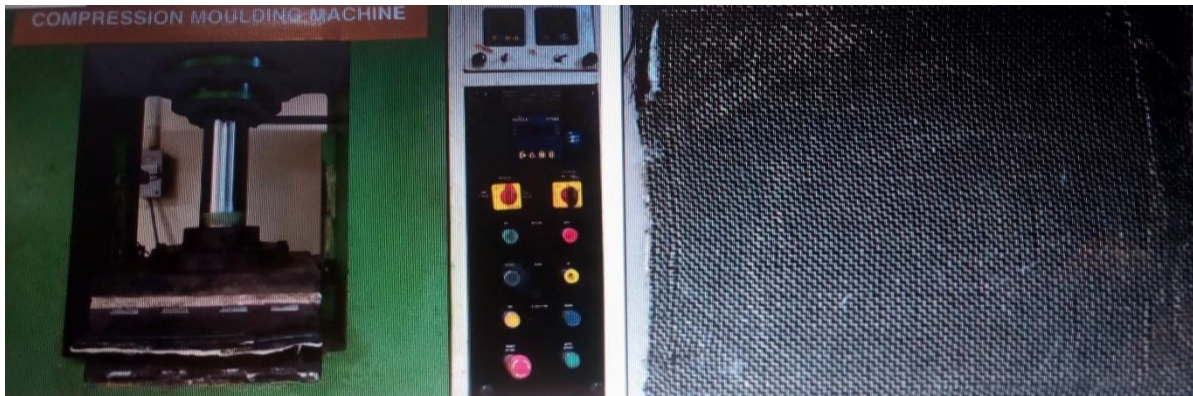


Figure 3: Schematic of the hybrid composite laminate

Fabrication was performed on a 350 mm × 350 mm plate of mild steel, degreased to remove impurities. A ratio of 60 : 40 fiber to resin was maintained. The fabrication started by depositing a thin layer of the resin – hardener mixture (100 : 35) at the bottom plate, then peel ply, and the first intraply fiber layer, followed by three layers of banana fibers, followed by intraply layer. The assembly was compressed in a moulding machine (Figure 4) and cured for 24 h. The final cured laminates were cut using an abrasive water jet machine to meet ASTM tensile, impact, and flexural standards, as shown in Figure 5.



(a) (b)
Figure 4 (a) : Compression moulding. (b) Final composite laminate.

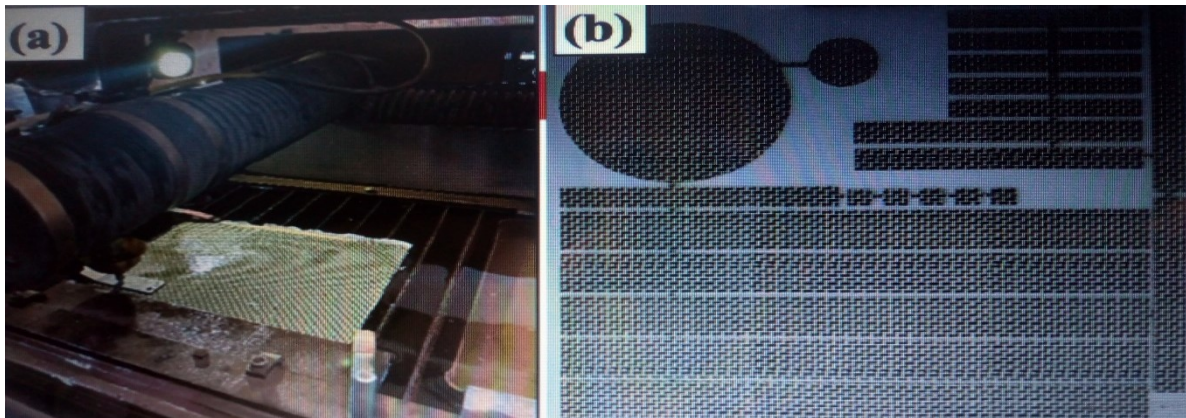


Figure 5 (a) : Water jet cutting. (b) Final cut laminate.

2.3. Testing Procedure

2.3.1. Void Test

The density of the composite was evaluated following the ASTM D792-20 (ASTM D792-20, 2020) standard. For this purpose, five square test samples with a 100 mm² area were prepared, and, using Archimedes' principle, density was measured. The mass of each sample was measured accurately with the help of an electronic balance, while the corresponding volume was obtained from the displacement of water. The experimental density values were then calculated from the mass -to-volume ratio. In addition, the theoretical density of the laminates was computed using Equation (1) (Okoronkwo et al. 2025):

$$\rho_{th} = \frac{1}{\frac{w_f}{\rho_f} + \frac{w_m}{\rho_m}} \tag{1}$$

where w_f , w_m , ρ_f , ρ_m are the weight fractions in (%) and densities of fiber and matrix in (g/m^2) respectively.

The void (%) was measured using Equation (2) ((ASTM D792-20, 2020), (Okoronkwo et al. 2024)).

$$\text{Void (\%)} = \frac{\rho_{th} - \rho_{ex}}{\rho_{ex}} \tag{2}$$

where ρ_{th} and ρ_{ex} are theoretical and experimental densities of the laminate in (g/m^2) respectively..

2.3.2. Short-Beam Shear Strength (SBSS) Test

The shear strength between the laminae in a composite laminate is a significant concern in engineering due to the risk of delamination failure. The tests were conducted using a Zwick/Roell machine, which had a maximum working capacity of 20 kN, to evaluate the adhesion strength between carbon-Kevlar intra-ply and banana fiber

layers of the composite. Samples measuring 25 mm in length and 4.4 mm in width were prepared and tested following the ASTM D-2344 (ASTM D2344/D2344M-13, 2022) standard for short-beam shear strength, as shown in Figure 6. The testing was conducted with a span length of 16 mm and a head displacement rate of 2 mm/min. By creating shear loads between layers, the machine determines the shear resistance, yielding important metrics on the material's interlayer adhesion performance.

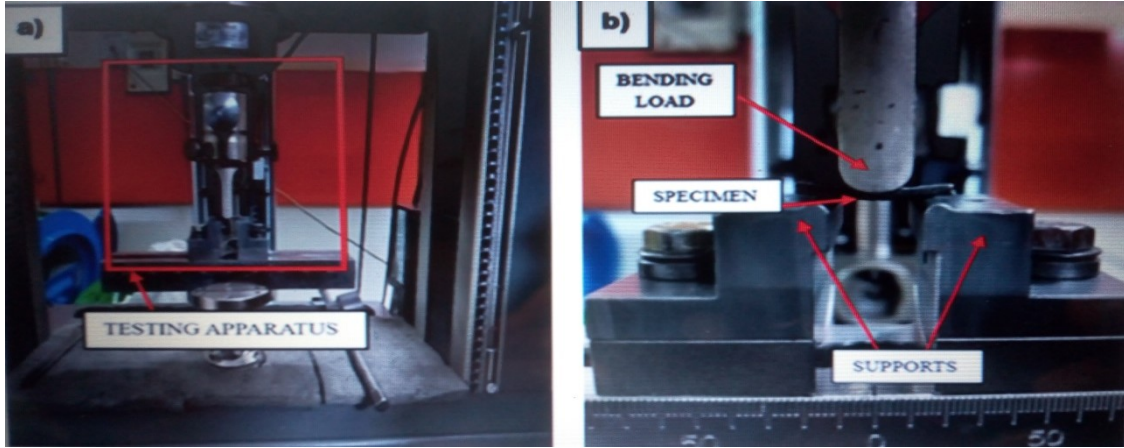


Figure 6(a) : SBSS test setup, (b) detailed view of the setup with sample.

2.3.3. Free-Vibration Test

Vibrational analysis determines the damping ratio and natural frequency of a composite through vibration testing. This kind of testing is important for understanding a material's ability to dissipate energy and withstand repeated vibrations and for identifying its natural frequencies, stiffness, and damping characteristics. Damping properties were evaluated according to ASTM E756-05 (ASTM E756-05, 2023) standard. Samples with dimensions of 250 mm × 25 mm were fixed at one end in a cantilever beam configuration, allowing the other end to remain unsupported (Figures 7 and 8).



Figure 7: Sample for vibration test

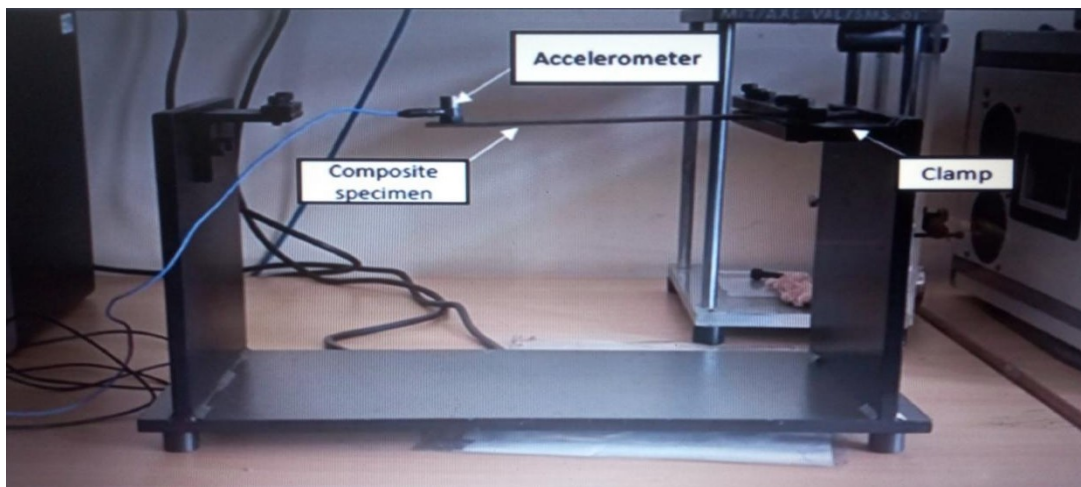


Figure 8: Vibration test apparatus

An impact hammer was used to induce free vibrations to the samples, and the stiffness (K) in (N/m), storage modulus (E_s) in (GPa), and natural frequency (f_n) in (Hz) were calculated by means of Equations (3) – (5),

$$K = \frac{3EI}{L^3} \tag{3}$$

$$f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \tag{4}$$

$$E_s = \frac{16\pi^2 f_n^2 L^3}{bh^3} \tag{5}$$

where E, I, L, m, b and h are Young’s modulus (MPa), moment of inertia ($g \cdot mm^2$), length (mm), mass (g), width (mm), and thickness (mm) of the sample, respectively.

These equations offer important information for understanding a material’s behavior under dynamic loading conditions and its structural potential. The logarithmic decrement approach is employed to calculate both the damping ratio and the logarithmic decrement. The logarithmic decrement (δ) measures the exponential decay rate of oscillation amplitudes in a damped system, derived from the ratio of the amplitudes of two consecutive peaks, X_1 and X_2 , as shown in Equation (6).

$$\delta = \frac{1}{n} \ln \left(\frac{X_1}{X_2} \right) \tag{6}$$

Here, n (Hz) is the number of oscillation cycles executed by the sample. The damping ratio (ζ) is a dimensionless descriptor representing the rate at which oscillations diminish in a system after being disturbed, with its relationship to logarithmic decrement expressed by Equation (7) (Namrata et al. 2024).

$$\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \tag{7}$$

2.3.4. Impedance Tube Test

This measurement is important for materials designed for sound insulation and noise control, as it directly reflects their ability to block or reduce unwanted noise. In this study, the transmission loss of the composite samples was evaluated using the impedance tube method. All testing procedures adhered to the guidelines provided by BSWA Technology (Scantek et al. 2025) and were conducted in compliance with the ISO 10534-2:1998 standard (ISO-10534, 2023). Circular samples with diameter of 99.5 mm and 29.5 mm were prepared to match the dimensions of the two different impedance tubes used in the experiment shown in Figure 9. Special attention was given to ensuring each sample fit tightly within the tube, eliminating any air gaps that could compromise the accuracy of the measurements.

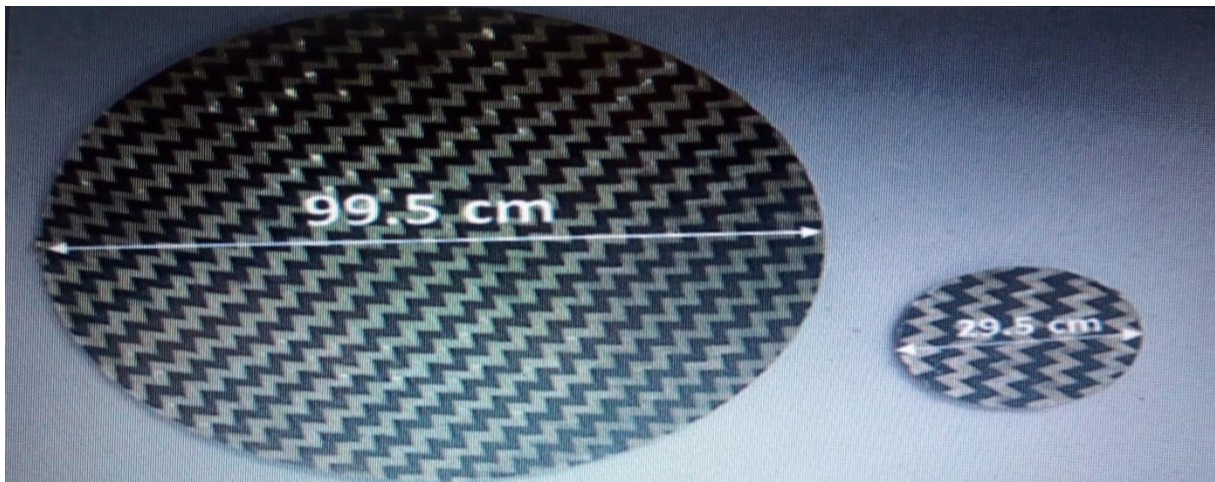


Figure 9: Sample for impedance tube

The experimental setup consisted of a loudspeaker capable of generating broadband noise, which was used as the sound source. Four microphones that had different sensitivities were placed at strategic points in big and small tubes at various intervals. These intervals were sustained for 10 min, using the transfer function technique over a frequency range of 63 Hz to an upper frequency limit of 6400 Hz. The microphones were placed at specific intervals to accurately capture the sound pressure levels on both sides of the sample, as shown in Figure 10.

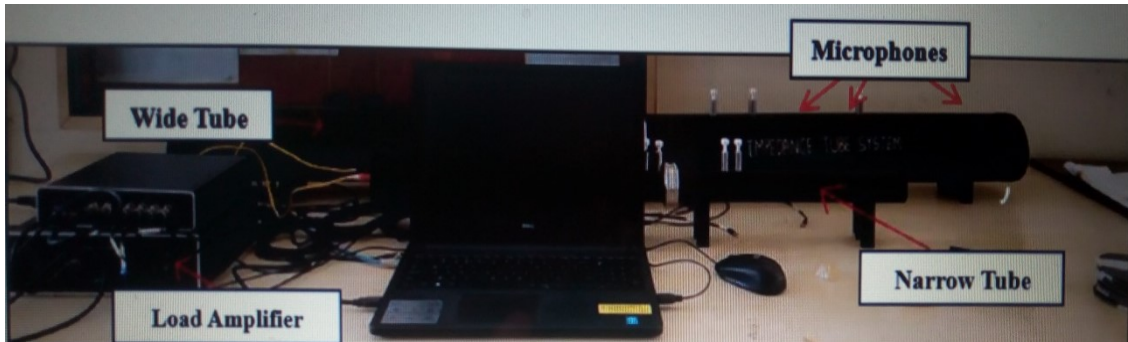


Figure 10: Impedance tube set-up

III. RESULTS AND DISCUSSION

3.1. Void Percentage

Voids represent empty regions in composites where polymer and fibers do not occupy the structure completely. Voids quantify the quality of fabrication in the sense that greater void content generally indicates fabrication defects. Voids can have a strong effect on mechanical failure in a critical application by offering a stress concentration site that lowers strength and longevity. The data are shown in Table 4 below.

Void contents (1.35 – 2.54 %) were well within allowable limits ($< 2 - 5$ %) for hybrid composites for engineering applications, signifying superior quality fabrication. $KMnO_4$ -treated composite had the least void content (1.35%). The reduction in void percentage in hybrid composites after NaOH and $KMnO_4$ treatment of banana fibers is primarily due to the removal of non-cellulosic components such as hemicellulose, lignin, pectin, waxes, and natural oils from the fiber surface (Kudva et al. 2024). This alkali treatment cleans the fibers, increasing surface roughness and exposing the cellulose micro-fibrils, which enhances fiber–matrix interfacial bonding. Improved adhesion facilitates more effective wetting and resin infiltration into the fiber surfaces during composite fabrication, thereby minimizing the formation of voids or air pockets within the composite. Additionally, the increase in fiber crystallinity and removal of amorphous substances lead to a more compact fiber structure, which further reduces void formation by allowing the matrix to better fill the available volume around fibers. This results in composites with lower void content and improved mechanical properties.

Table 4: Void fractions.

Composite	Experimental Density, ρ_{ex} (Gram per Cubic Centimetre, g/cc3)	Theoretical Density, ρ_{ex} (Gram per Cubic Centimetre, g/cc3)	Void (%)
Untreated	1.57	1.61	2.54
NaOH-treated	1.43	1.46	2.09
KMnO4-treated	1.48	1.50	1.35

3.2. Short-Beam Shear Strength (SBSS)

Figure 11 presents the SBSS test results for the fabricated hybrid composites. The untreated composite exhibited an inter-laminar shear strength (ILSS) of 14.27 ± 1.72 MPa, reflecting the inherent challenge with natural fibers where weak fiber–matrix adhesion arises due to impurities like lignin and waxes on the fiber surface. Treatment with 0.5 % $KMnO_4$ increased the ILSS to 17.65 ± 1.84 MPa, a significant improvement attributed to the oxidative removal of surface contaminants, which enhanced fiber surface roughness and chemical compatibility with the epoxy matrix, promoting better interfacial bonding. The 5 % NaOH treatment resulted in the highest ILSS of 19.52 ± 2.03 MPa, indicating superior removal of hemicellulose and lignin, increased exposure of hydroxyl groups, and greater surface roughness, all of which bolster fiber wettability and mechanical interlocking, leading to more effective stress transfer at the interface.

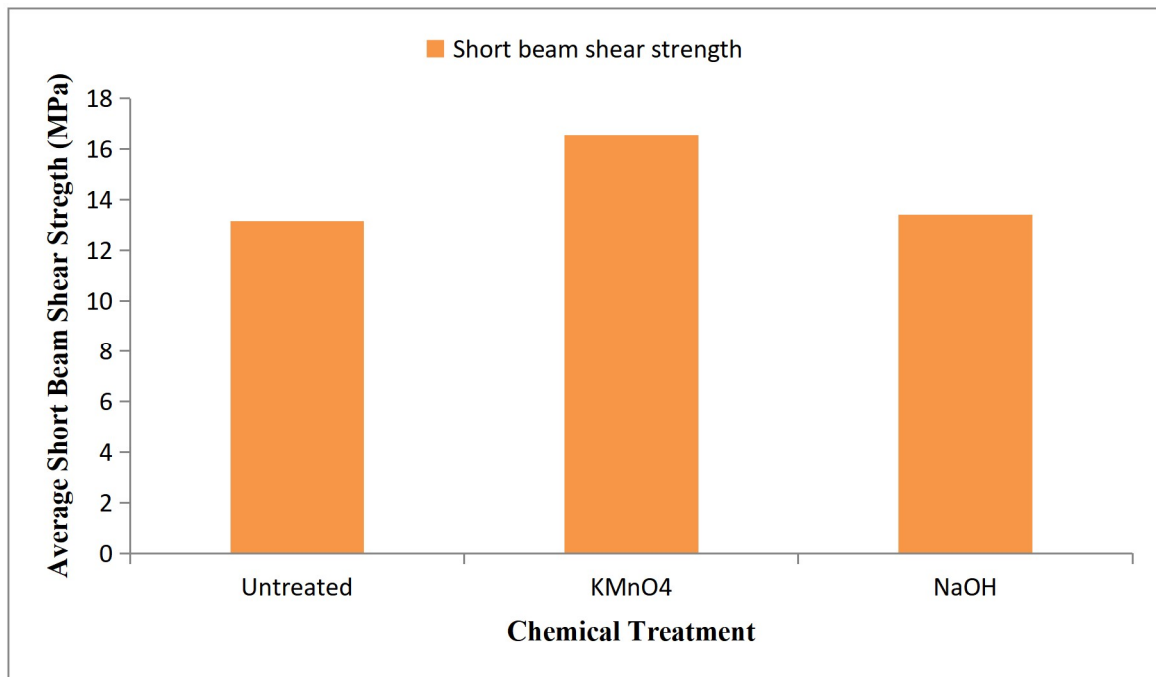


Figure 11: Short-beam shear strength test results.

The significant rise in SBSS to 9.52 MPa for NaOH-treated laminates is a direct consequence of improved fiber–matrix adhesion. The NaOH treatment, known as mercerization, effectively removed surface lignin and hemicellulose, exposing more hydroxyl groups on the cellulose surface. This chemical cleaning not only increased the surface roughness for better mechanical interlocking but also promoted stronger hydrogen bonding at the interface, thereby increasing the force required to induce interfacial shear failure (SBSS).

The sandwich structure benefited from the high strength and stiffness of the carbon– Kevlar outer layers, which act as reinforcing skins, while the banana fiber core contributes to shear load resistance. The improved fiber–matrix interface due to chemical modification facilitates more efficient load transfer between the core and skins, reducing delamination and enhancing damage tolerance under shear loading. This enhancement in ILSS is critical for applications requiring strong inter-laminar adhesion to prevent premature failure.

These findings align closely with the existing literature that highlights the effectiveness of chemical treatments in reinforcing natural fiber composites, especially in hybrid systems combining natural and synthetic fibers (Yahiya et al. 2023). Moreover, microscopy studies (Figure 12) underline the cleaner, well-impregnated fiber surfaces and reduced defects that result from these treatments, confirming their role in mechanical property enhancement. Overall, the results underscore the practical value of surface treatment protocols in optimizing the structural performance of eco-friendly hybrid composites based on banana fabric and high-performance carbon–Kevlar layers, thereby expanding their potential for advanced engineering applications where weight, strength, and sustainability are critical factors.

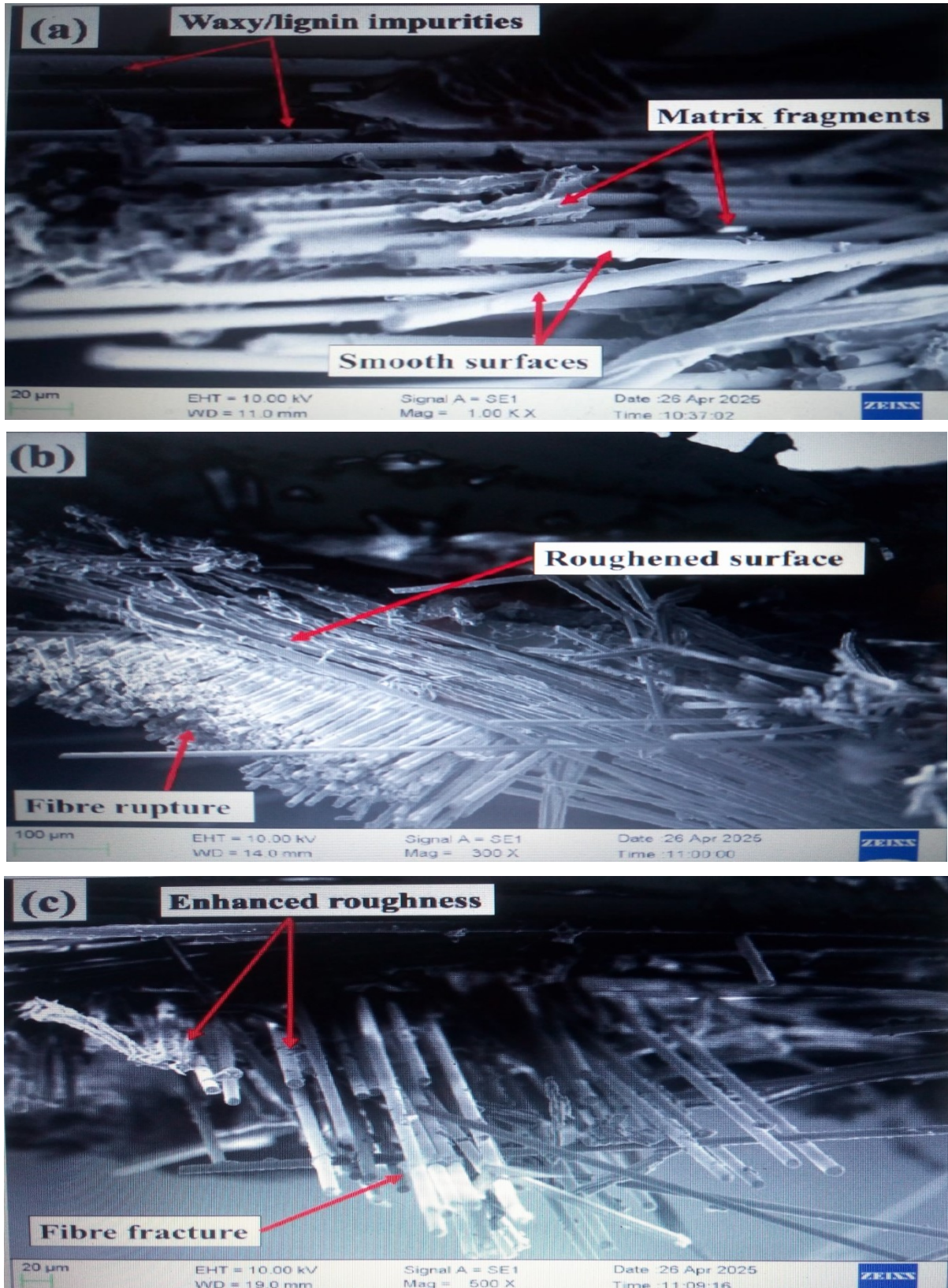


Figure 12: SEM images of fractured SBSS test samples: (a) untreated (1.00kx), (b) KMnO₄-treated (300x) and (c) NaOH-treated (500x).

3.3. Impedance Tube Test

The acoustic transmission loss (TL) data presented in Figure 13 indicates a clear frequency-dependent behaviour for the hybrid composites with different banana fiber treatments. All three samples—untreated, NaOH--treated, and KMnO_4 -treated demonstrate increasing TL values as frequency increases, which is consistent with the physics of acoustic wave attenuation in layered composites.

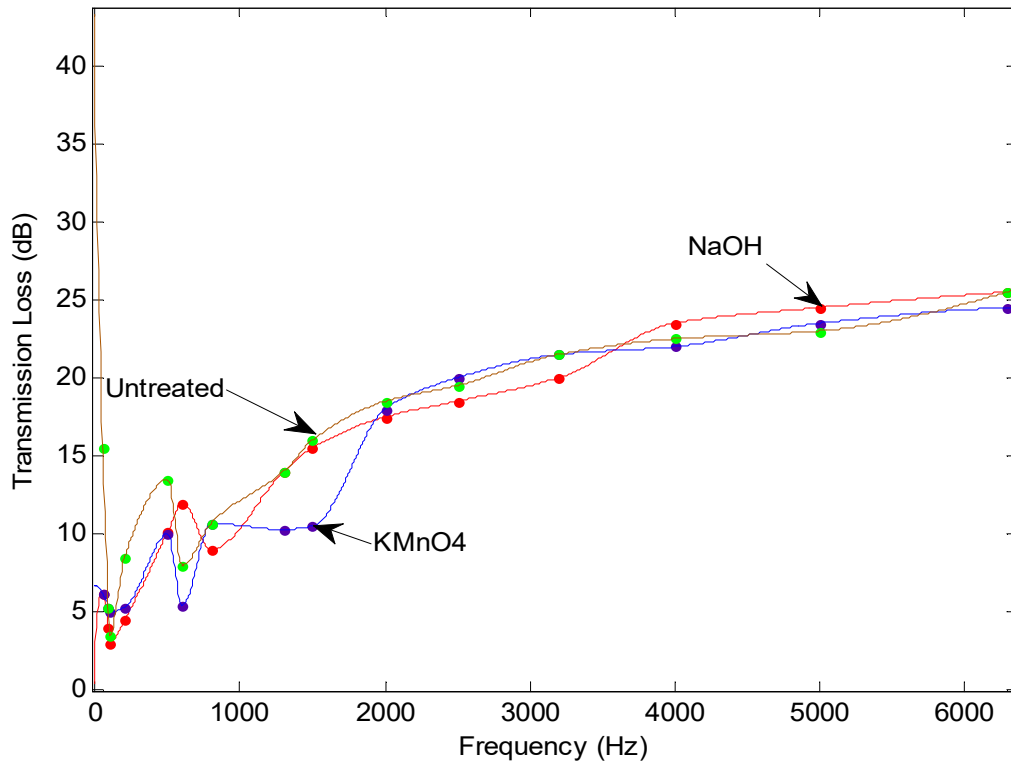


Figure 13: Impedance tube test result comparison.

At low frequencies (50 – 200 Hz), the KMnO_4 -treated sample exhibits the best acoustic insulation performance, achieving a TL of 15.5 dB at 50 Hz, which exceeds that of both the untreated and NaOH-treated samples. This superior performance is likely due to the effect of KMnO_4 treatment enhancing the fibre–matrix interface and promoting better mechanical damping of vibrational energy. The untreated sample consistently shows the lowest TL values across all frequency ranges, reaffirming that the absence of chemical modification results in poorer acoustic performance due to weaker interfacial bonding and less-effective energy dissipation.

In the mid-frequency range (600 – 3000 Hz), the KMnO_4 -treated composite continues to outperform the others, reaching a TL of approximately 16 dB at 1500 Hz, reflecting consistent acoustic insulation improvement. The untreated sample still performs reasonably well in this range (5.4 – 10.5 dB), but the NaOH-treated sample underperforms, with TL rarely exceeding 4 dB until it reaches 1500 Hz. This suggests that while NaOH treatment improves mechanical properties, its effect on acoustic insulation in the mid-frequency range may be less pronounced or dependent on treatment parameters.

At high frequencies (1000 – 6300 Hz), NaOH treatment demonstrates competitive performance, especially at frequencies above 4000 Hz, where the TL rises notably, indicating effective acoustic insulation at higher frequencies. However, KMnO_4 treatment remains the most effective overall across the entire frequency spectrum, particularly excelling in mid and low-frequency ranges, where it provides significant improvements. The untreated material remains the least effective, especially at low frequencies, underscoring the importance of chemical surface modification to enhance acoustic insulation properties of banana fiber/carbon–Kevlar hybrid composites.

The transmission loss (TL) value of 15.5 dB at 50 Hz obtained in this study for the banana fiber/carbon–Kevlar hybrid composite is comparable to or better than the TL values reported in the literature for similar natural fiber

composites such as jute-, kenaf-, and flax based materials. For example, flax composites generally exhibit higher sound absorption and transmission loss than jute composites, due in part to their higher fiber volume fraction and microstructure. The reported TL values for jute and flax composites in the low frequency range (around 60 – 100 Hz) typically range from about 10 to 15 dB, with variations depending on fabric architecture and fiber treatment. Kenaf-based hybrid composites have been shown to achieve TK values that are comparable to or slightly lower than those of jute/flax composites at low to middle frequencies, with improvements possible via chemical surface treatments ((Shankar et al. 2025), (Senthilrajan et al. 2024)).

Overall, these results highlight that $KMnO_4$ treatment offers superior acoustic damping properties, promoting better transmission loss across a broad frequency range. NaOH-treatment provides moderate enhancement, particularly at higher frequencies. This demonstrates that chemical treatments play a vital role in modifying the interface and microstructure of natural fiber composites, thereby significantly improving their acoustic insulation characteristics. These findings have important implications for the development of multifunctional sandwich composites, where both mechanical strength and acoustic performances are critical design criteria.

3.4. Free-Vibration Test

The dynamic mechanical performance of natural fiber composites is a critical factor in determining their suitability for structural applications, especially those involving vibrations and sound insulation. In this study, the effect of chemical treatments on the natural frequency, stiffness, logarithmic decay, and damping ratio of banana fiber composites, which were hybridized with carbon-Kevlar intra-ply fabrics, was investigated to understand how surface modification influences the composite’s dynamic response. Free vibration test results are presented in Table 5.

The acceleration amplitude vs. time plots of untreated as well as NaOH -and $KMnO_4$ -treated samples are presented in Figure 14, Figure 15, and Figure 16, respectively. The untreated composite showed a natural frequency of 26.08 Hz and stiffness of 7780.23 N/m, with very low damping ratio (0.00716). These low-damping properties indicate weak fiber–matrix interfacial bonding attributed to the presence of lignin, waxes, and hemicellulose on the banana fiber surfaces, which hinders efficient load transfer and limits energy-dissipation mechanisms in the composite. Therefore, the untreated composite’s ability to attenuate vibrations is considerably weaker, indicating that its application might be limited in environments where vibration control is essential.

Table 5: Vibration analysis test results.

Composite Type	Natural Frequency (Hz)	Stiffness (N/m)	Damping Ratio (ζ)
Untreated	26.08 ±1.43	7780.23±268	32 0.00716± 0.0002864
NaOH-treated	28.68 ±1.81	9480.51±303.51	0.00398±0.000159
$KMnO_4$ -treated	22.12±1.67	5640.84±245.84	0.0557±0.00228

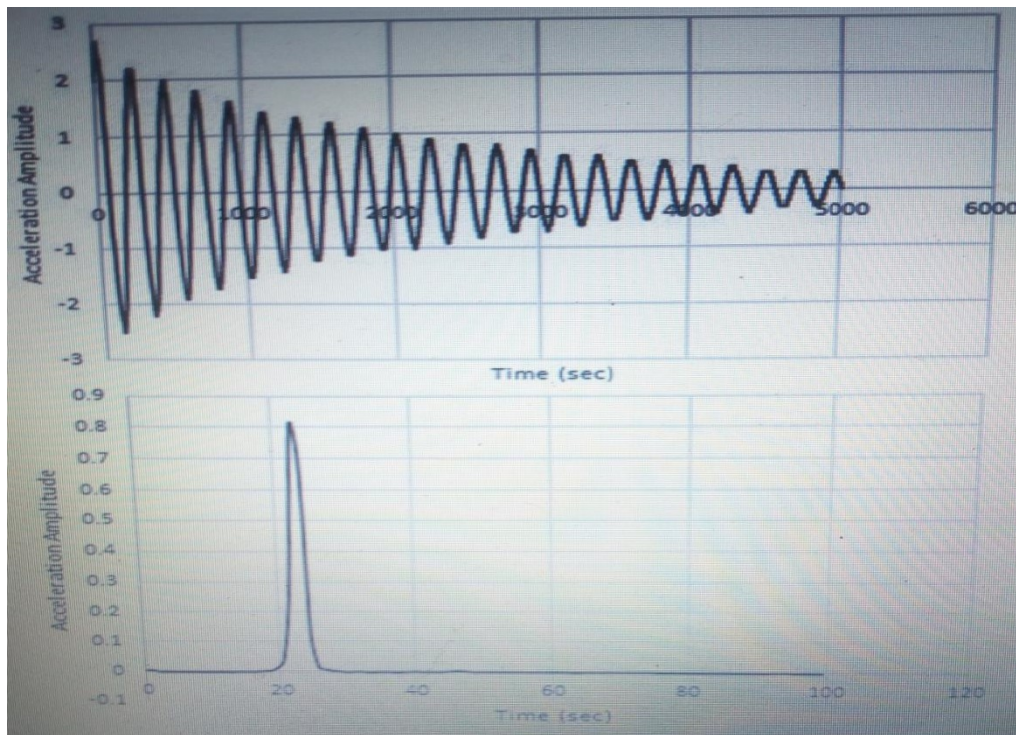


Figure 14: Untreated fibre laminate.

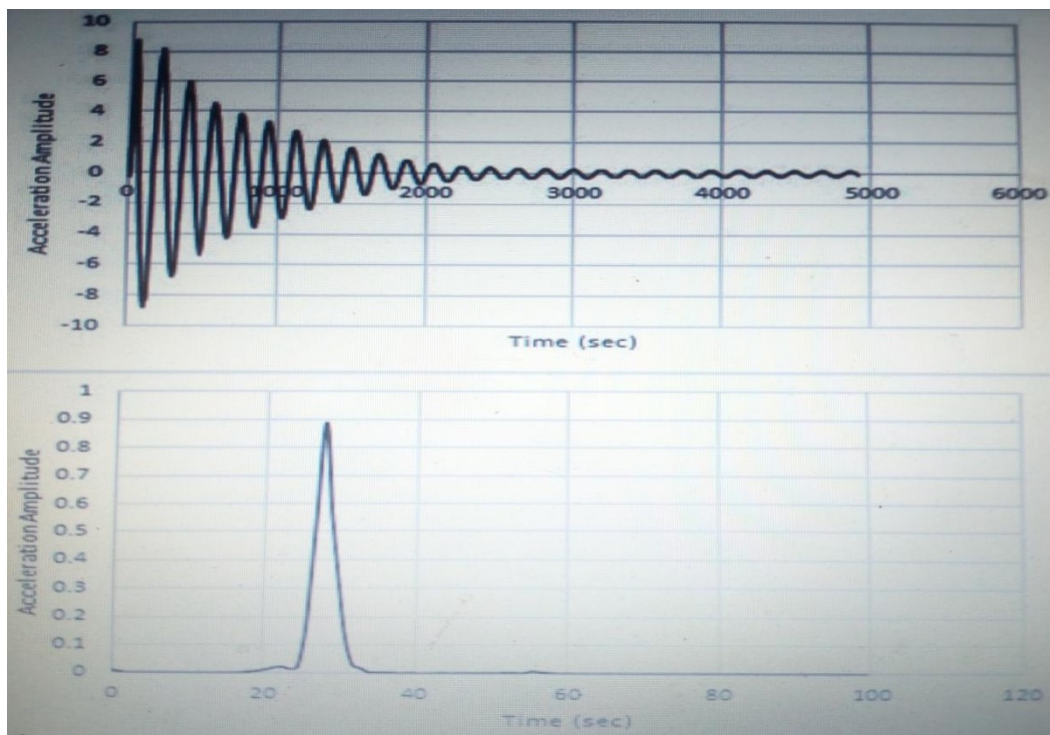


Figure 15: NaOH-treated laminate.

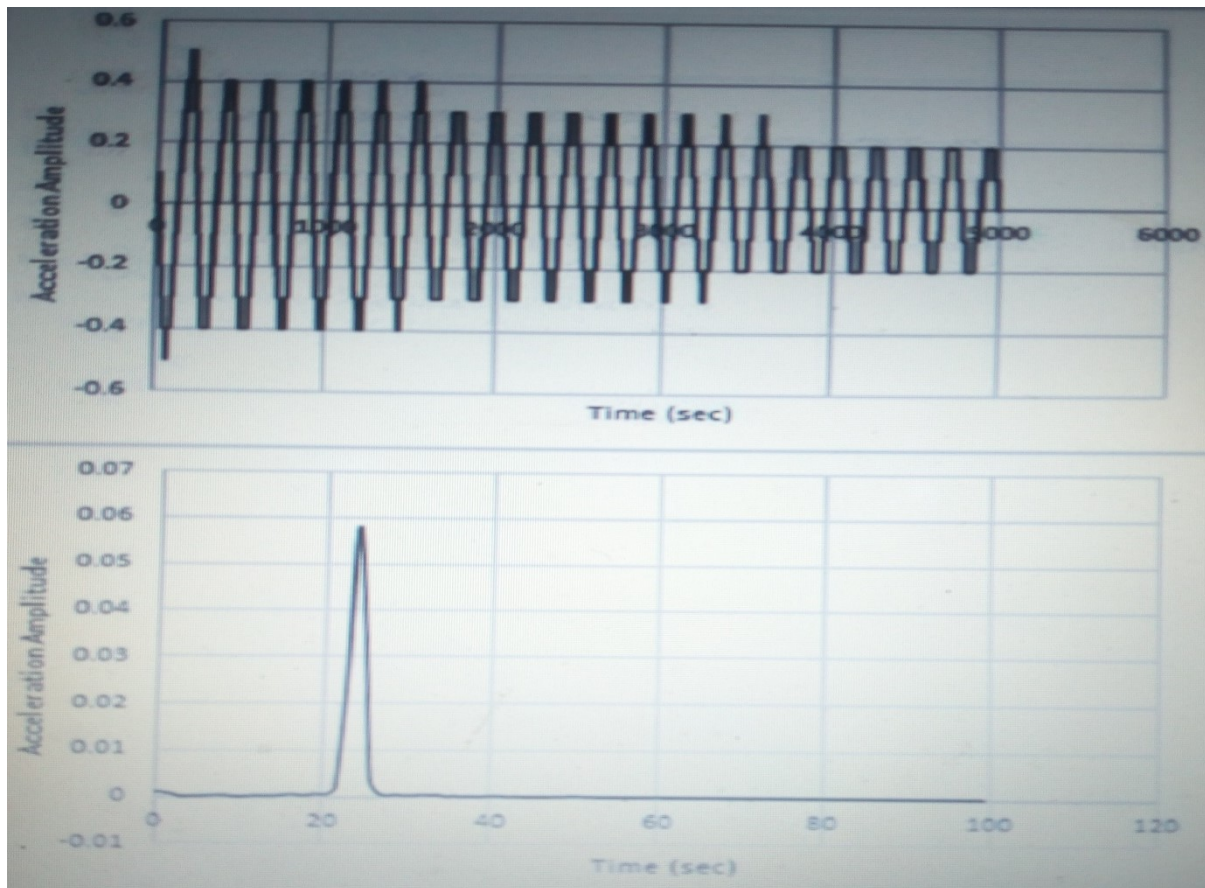


Figure 16: KMnO_4 -treated laminate

The 21.8 % increase in stiffness (as indicated by the jump in natural frequency) in NaOH-treated composites is interpreted as a function of the improved efficiency of stress transfer. When fibre–matrix adhesion is weak (untreated), the interface acts as a source of discontinuity, limiting the composite’s ability to resist deformation. The robust chemical and mechanical bonding achieved via NaOH-treatment ensures that the stiff carbon–Kevlar skins and the banana fiber core bear the dynamic load more effectively as a single structural unit, resulting in a higher overall modulus and, consequently, increased stiffness.

The surface treatment of the banana fibers using NaOH significantly altered these properties. The natural frequency increased to 28.68 Hz, and stiffness enhanced to 9480.51 N/m, indicative of a stiffer and more resilient composite structure. The damping ratio improved to 0.00398, reflecting enhanced energy dissipation abilities. The alkali treatment removes amorphous substances like lignin and hemicellulose, roughens the fiber surface, and exposes hydroxyl groups that chemically interact more effectively with the epoxy matrix, thereby improving interfacial bonding. This improved interface strengthens load transfer paths and introduces additional mechanisms for dissipating vibrational energy, such as interfacial friction and micro damage diffusion, which contribute to the elevated damping performance.

In contrast, KMnO_4 treatment resulted in a composite with a lower natural frequency of 22.12 Hz and stiffness of 5640.84 N/m but higher damping characteristics, with a damping ratio of 0.0557, the highest among the samples. This suggests that although KMnO_4 treatment reduces the structural stiffness slightly, it enhances the composite’s ability to dissipate vibrational energy more effectively. The oxidative properties of KMnO_4 modify the fiber surface, potentially creating a more compliant and roughened interfacial layer that facilitates improved energy conversion from mechanical vibrations to heat, thus substantially increasing damping capacity. This effect is highly beneficial for applications requiring vibration attenuation rather than just structural stiffness. The different effects of NaOH and KMnO_4 treatments illustrate the trade-offs in composite design between stiffness and damping. NaOH -treatment promotes stronger bonding and higher rigidity, which increase natural frequencies and stiffness but with comparatively lower damping improvements. KMnO_4 -treatment, on the other hand, prioritises energy absorption and dissipation, making it suitable for damping-critical applications despite a reduction in stiffness.

The observed increase in the damping ratio produced by the NaOH treatment provides critical interpretive evidence regarding energy dissipation. Damping in polymer composites is heavily governed by the interfacial region. For untreated laminates, the low damping is attributed to poor adhesion, leading to interfacial slip (frictional energy loss) that is not optimized. Conversely, the stronger interface in the treated composites allows for efficient viscoelastic energy dissipation through constrained movement of the polymer chains adjacent to the fiber surface, where the maximum shear stress and subsequent energy loss occur. This constrained motion within a well-bonded interphase is a superior mechanism for dampening vibrations than simple frictional slip.

These findings underscore the importance of fiber surface chemistry in tailoring the dynamic mechanical properties of natural fiber hybrid composites. The ability to manipulate stiffness and damping independently by selecting an appropriate chemical treatment expands the applicability of banana fiber/carbon–Kevlar hybrid composites in multifunctional roles where mechanical strength and vibration control are both critical. This work highlights the potential for designing sustainable, high-performance composites with customisable dynamic properties through targeted chemical surface modifications.

Figure 14 presents the acceleration amplitude versus time plot for the untreated banana fiber/carbon–Kevlar laminate. The untreated composite shows a natural frequency of 26.08 Hz and stiffness of 7780.23 Nm, with a low damping ratio of 0.00716. These results indicate that untreated fibers lead to weak fiber–matrix interfacial bonding due to residual lignin and waxes, causing limited energy dissipation and poor vibrational attenuation. Application-wise, such laminates will struggle in environments demanding vibration control, as persistent structural oscillations may accelerate failure or cause functional instability.

Figure 15 displays the vibrational response for laminates where banana fibers are treated with NaOH. The natural frequency increases to 28.68 Hz, and stiffness rises to 9480.51 Nm, with a moderate damping ratio of 0.00398. This jump in frequency and stiffness (21.8 % over untreated) highlights improved stress transfer due to superior fiber–matrix adhesion, resulting from the removal of hemicellulose and lignin and enhanced chemical interaction between the fiber and resin. Such laminates are suitable for dynamic structural roles requiring both rigidity and moderate damping, as the alkali treatment ensures integrated load bearing and more effective energy dissipation.

Figure 16 provides the vibrational plot for the KMnO_4 -treated laminate. KMnO_4 -treatment results in a reduced natural frequency (22.12 Hz) and lower stiffness (5640.84 Nm) compared to the previous two but dramatically increases the damping ratio to 0.0557, the highest among all configurations. The oxidative treatment creates a compliant, roughened interface that, although less rigid, is highly effective at converting mechanical vibrations into heat, thereby maximizing energy dissipation. These laminates are best for applications where vibration damping is the primary requirement, rather than maximum stiffness. For example, in noise isolation panels or vibration control systems.

IV. CONCLUSIONS

This investigation analyzed the effects of untreated and chemically treated samples on the SBSS, free-vibration, and acoustic behaviour of hybrid composites. The key findings are as follows:

- KMnO_4 -treated composites showed the lowest void content (1.35 %), a 46.85 % reduction compared to untreated (2.54 %) and a 35.41% reduction compared to NaOH-treated (2.09 %) composites, indicating superior fabrication quality.
- Chemical treatments significantly enhanced ILSS of banana-fiber-reinforced carbon–Kevlar composites, with NaOH treatment increasing the ILSS by 36.7 % (from 14.27 MPa to 19.52 MPa) and KMnO_4 treatment increasing it by 23.7% (to 17.65 MPa).
- Vibration analysis showed NaOH treatment increased stiffness by 21.8 % and natural frequency by 9.9 %, while KMnO_4 treatment enhanced the damping ratio from 0.00716 to 0.0557 compared to untreated composites, indicating superior vibration energy dissipation.
- Acoustic performance improved markedly with KMnO_4 treatment, achieving a transmission loss (TL) increase of up to 40% at low frequencies (63 Hz) relative to untreated composites.
- Surface morphology analysis confirmed improved fiber–matrix bonding and reduced defects after chemical treatments, directly correlating with mechanical and functional property enhancement.
- These improvements underline the effectiveness of targeted chemical treatments in developing sustainable, multifunctional hybrid composites with enhanced mechanical strength, vibration damping, and acoustic insulation for advanced engineering applications.

- This work demonstrates the potential of banana fiber and carbon–Kevlar intra-ply hybrid composites for lightweight structural applications. Future studies should focus on developing finite element models to predict mechanical behaviour and optimize designs. Additionally, evaluating durability under humid and variable environmental conditions is critical to ensure long-term reliability and broaden practical use.

- The limitations of this study include the limited range of chemical treatments investigated, the environmental testing confined to ambient conditions without controlled temperature or humidity variations, and challenges related to industrial scalability such as consistent fiber quality and process optimization. These factors restrict the immediate applicability of results, indicating the need for future work exploring alternative treatments, more extensive environmental testing, and scalable manufacturing methods.

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Competing interests

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